FATIGUE LIFE EVALUATION OF IN-SERVICE STEEL BRIDGES BY USING BI-LINEAR S-N CURVES

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ABSTRACT: The in-service steel bridges are often required to carry increasing volume of traffic and heavier trucks or freight trains. More attention should be paid to possible fatigue damages of such structures. It has been reported that for many structure details with an equivalent stress range below the constant amplitude fatigue limit (CAFL) and free of fatigue cracks, calculations show that the remaining fatigue life has been exhausted. This condition indicates that it could be too conservative to predict the remaining fatigue life of in-service steel bridges by utilizing the equivalent constant amplitude stress ranges with the direct extension of S-N curves of AASHTO specifications with a slope of -3 to below the CAFL. This over-prediction of fatigue damage may lead to unnecessary rehabilitation and maintenance actions. For a better fatigue life evaluation and prediction, a set of bi-linear S-N curves with a break at the CAFL for the AASHTO fatigue strength categories and with a slope of -4 below, has been proposed for fatigue life evaluation of in-service structures. This paper applies the concept of the equivalent constant amplitude stress range for bi-linear curves to AASHTO specifications and Eurocode. Cases of fatigue evaluation of in-service steel bridge components are studied by correlating the field-measured live-load stresses with the bi-linear S-N curves. Comparative results from the bi-linear S-N curve approach, the current AASHTO specifications and Eurocode approach are presented.

Keywords: Steel bridges, Fatigue life evaluation, Bi-linear S-N curve, Constant amplitude fatigue limit, Equivalent stress range

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1. INTRODUCTION

For many in-service steel bridges, fatigue is a primary safety concern and each structural detail of a steel bridge has its evaluated fatigue strength according to the current design codes and specifications. The fatigue strength categories (S-N curves) define the relationship between the applied primary stress range (live-load stress range) of constant amplitude and the number of stress cycles when fatigue damage is expected.

The current procedure for predicting the remaining fatigue life of steel bridges by AASHTO specifications [1] utilizes an equivalent constant amplitude stress ranges (S_{re}) with the direct extension of the S-N curves of a single slope of -3 to below the constant amplitude fatigue limit (CAFL) for the different detail categories. In order to calculate the S_{re}, a live load stress range spectrum or histogram for the structural detail should be developed to correlate with the governing S-N curve [2]. The fatigue life evaluated by this approach is generally adequate for bridge safety management [3]. Yet this approach was found to be conservative, often resulting in over-prediction of fatigue damage and may lead to unnecessary rehabilitation or maintenance actions. A number of details have been found to be free of cracks although the calculated remaining fatigue life by the current procedure showed that the details should be suffered from cracks [4]. For this reason, the direct extension of S-N curves from above to below the CAFL was examined analytically [5]. The result is a set of bi-linear S-N curves with a break at the CAFL and a slope of -4 below for the

fatigue strength categories in AASHTO. The utilization of bi-linear S-N curves is being considered by bridge engineers [6].
The fatigue life evaluation of in-service steel bridges should be conducted based on the performance of the bridge structure under actual live loads. This is because the assumptions made on service loads during the design stage usually do not provide sufficiently accurate representation of the actual live load history. Even more importance is the fact that almost all connections and joints of bridge components do not behave exactly in the service state as considered in design according to the strength state. The behavior of a bridge structure under service loads at specific positions of these loads on the bridge can be analyzed using finite element models. However, the positions of the trucks, the size and weight of these truck loads are various. Therefore, direct monitoring of field-measured live-load stresses at fatigue-prone structural details is best suited for the fatigue life evaluation.

2. FATIGUE LIFE EVALUATION BY USING BI-LINEAR S-N CURVES

2.1 The Concept of Bi-linear S-N Curves

The AASHTO S-N curves are typically established based on the results of numerous experimental studies and the values of CAFLs are associated with the stress intensity factor range threshold, ΔK_{th} [7]. The stress intensity factor range can be expressed as Eq. (1).

$$\Delta K = \Delta\sigma \cdot \sqrt{\pi a} \cdot Y \tag{1}$$

And it follows as Eq. (2).

$$\Delta K_{\mathrm{th}} = CAFL \cdot \sqrt{\pi a_{\mathrm{i}}} \cdot Y \tag{2}$$

Where $\Delta\sigma$ is the applied stress-range; a is the size of fatigue crack; a_{i} is the hypothetical initial value of crack size associated with ΔK_{th}; and Y is a non-dimensional function of the geometry including various factors such as finite width factor, non-uniform stresses factor, free surface effect factor and crack shape factor.

Stress range cycles in a spectrum with amplitudes higher than the CAFL would cause micro-scaled increase of the crack to greater than a_{i} and, as indicated in Eq. 2 , the value of CAFL would decrease as the crack size increases because the value of ΔK_{th} remains constant. It is concluded that this condition would subsequently allow slightly lower magnitude stress-range cycles in a spectrum to contribute to the crack growth [5, 8-9].

By using this concept to examine the repeated cumulative damage of a few stress range histograms, Crudele & Yen [5] analytically examined the extension of S-N curves below the CAFL of four different AASHTO categories (B, C, D, and E). They found that the computed fatigue lives above the CAFL agreed well with the fatigue lives associated with the AASHTO S-N curves for all categories and, however, fatigue lives below the CAFL have to be re-estimated. Results indicated that the average slope of extended lines of the fatigue strength categories is -4 below the CAFL. This slope is recommended for use. Figure 1 shows the derived bi-linear S-N curves for all AASHTO categories [6]. The S-N curve of structural detail Category C' is shown in Figure 2 with some experimental data [10]. The result of Figure 2 provides confidence for the application of bi-linear S-N curves.

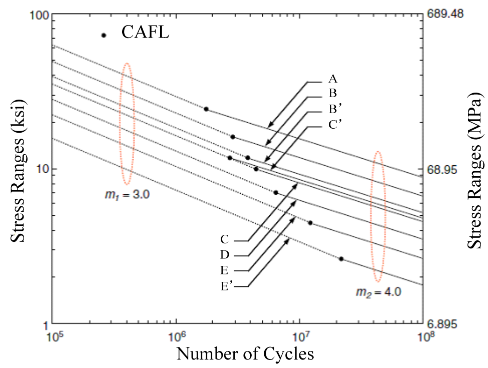


Figure 1. Bi-linear S-N Curves for All Fatigue Categories [6]

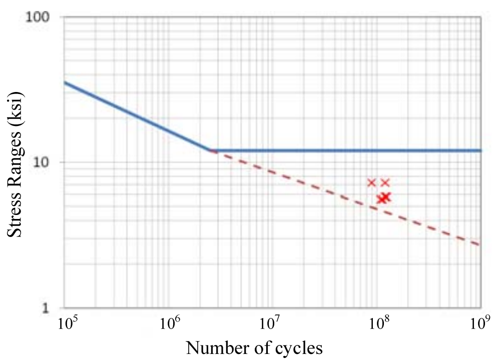


Figure 2. Bi-linear S-N Curves for Category C′ [10]

It is worth noticing that Europe has adopted a set of tri-linear S-N curves with a slope of m when stress ranges are above CAFL, and the second slope below CAFL is suggested as $2m$-1 by Haibach [11-12], while m=3 is used in Eurocode 3[13] with a horizontal line after the cut-off limit at 100 million cycles, as shown in Figure 3. For other details, the first slope was also found to be m_1=4 and the second slope is $m_2 = 2m_1 - 1 = 7$ for riveted and bolted details.

2.2 Evaluation approach

According to Palmgren-Miner linear damage hypothesis, Eq. (3) indicates fatigue failure.

$$D = \sum_i \frac{n_i}{N_i} = 1 \tag{3}$$

Where n_i is number of cycles accumulated at stress range level i, for which damage would occur when the stress is applied N_i cycles; D is the fraction of life consumed by exposure to the cycles at the different stress range levels.

For a bi-linear S-N curve with a break at the magnitude of stress range K and the slopes of m_1 and m_2 above and below K, respectively, the application of Palmgren-Miner linear damage hypothesis shows in Eq. (4).

$$D = \sum_i \frac{n_i}{N_i} + \sum_j \frac{n_j}{N_j} = 1 \tag{4}$$

Where the subscripts *i* and *j* mean stress cycles above and below the break at *K*, respectively. Using the stipulation of equivalent stress range by Schilling et al. [14], Eq. (5) can be acquired.

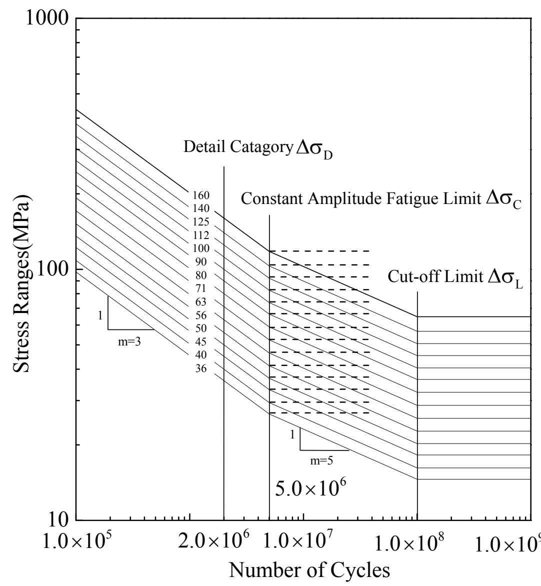


Figure 3. The Tri-linear S-N Curves in Eurocode 3 [13]

$$D = \sum_i \frac{n_i}{N_i} + \sum_j \frac{n_j}{N_j} = \frac{\sum_{i,j}(n_i + n_j)}{N_e} = 1 \tag{5}$$

The symbol N_e is the calculated fatigue life using the equivalent constant amplitude stress range S_{re}. The sum of all stress cycles is $\sum_{i,j}(n_i + n_j) = N$ and the equations for the two segments of the S-N curves are shown in Eq. (6).

$$N_i = A_{m_1} \cdot S_i^{-m_1} \quad \text{and} \quad N_j = A_{m_2} \cdot S_j^{-m_2} \tag{6}$$

Corresponding to N_e for single-slope S-N curves, the equations of the segments of the bi-linear one are shown in Eq. (7).

$$N_e = \begin{cases} A_{m_1} \cdot S_{\mathrm{re}m_1m_2}^{-m_1} & \text{for} \quad S_{\mathrm{re}m_1m_2} \geq K \\ A_{m_2} \cdot S_{\mathrm{re}m_1m_2}^{-m_2} & \text{for} \quad S_{\mathrm{re}m_1m_2} < K \end{cases} \tag{7}$$

$S_{\mathrm{re}m_1m_2}$ with a double subscripts, m_1 and m_2, is the equivalent constant amplitude stress range for bi-linear S-N curves. By substituting Eq. (6) and Eq. (7) into Eq. (5), and solving for $S_{\mathrm{re}m_1m_2}$, Eq. (8) can be acquired.

$$S_{\mathrm{re}m_1m_2}=\begin{cases}\left(\sum_i \frac{n_i}{N}\cdot S_i^{m_1}+\frac{A_{m_1}}{A_{m_2}}\sum_j \frac{n_j}{N}\cdot S_j^{m_2}\right)^{1/m_1} & \text{for } S_{\mathrm{re}m_1m_2}\geq K\\ \left(\frac{A_{m_1}}{A_{m_2}}\sum_i \frac{n_i}{N}\cdot S_i^{m_1}+\sum_j \frac{n_j}{N}\cdot S_j^{m_2}\right)^{1/m_2} & \text{for } S_{\mathrm{re}m_1m_2}<K\end{cases} \tag{8}$$

By using the stress cycle, the coefficients ratio, N_k, in the Eq. 8 can be determined at the break of the S-N curve, shown in Eq. (9).

$$N_k = A_{m_1}K^{-m_1}=A_{m_2}K^{-m_2} \tag{9}$$

This leads to Eq. (10).

$$\frac{A_{m_1}}{A_{m_2}}=K^{m_1-m_2},\quad \frac{A_{m_2}}{A_{m_1}}=K^{m_2-m_1} \tag{10}$$

In this way, $S_{\mathrm{re}m_1m_2}$ can be determined by Eq. (11).

$$S_{\mathrm{re}m_1m_2}=\begin{cases}\left(\sum_i \frac{n_i}{N}\cdot S_i^{m_1}+K^{m_1-m_2}\sum_j \frac{n_j}{N}\cdot S_j^{m_2}\right)^{1/m_1} & \text{for } S_{\mathrm{re}m_1m_2}\geq K\\ \left(K^{m_2-m_1}\sum_i \frac{n_i}{N}\cdot S_i^{m_1}+\sum_j \frac{n_j}{N}\cdot S_j^{m_2}\right)^{1/m_2} & \text{for } S_{\mathrm{re}m_1m_2}<K\end{cases} \tag{11}$$

Specifically, for a bi-linear S-N curve with the break at the CAFL (i.e. K = CAFL) and the slopes above and below CAFL of the S-N curve are $m_1 = 3$ and $m_2 = 4$, respectively. The equations for the equivalent constant amplitude stress ranges $S_{\mathrm{re}34}$ are expressed by Eq. (12).

$$S_{\mathrm{re}34}=\begin{cases}\left(\sum_i \frac{n_i}{N}\cdot S_i^{3}+\frac{\sum_j \frac{n_j}{N}\cdot S_j^{4}}{CAFL}\right)^{1/3} & \text{for } S_{\mathrm{re}34}\geq CAFL\\ \left(CAFL\cdot\sum_i \frac{n_i}{N}\cdot S_i^{3}+\sum_j \frac{n_j}{N}\cdot S_j^{4}\right)^{1/4} & \text{for } S_{\mathrm{re}34}<CAFL\end{cases} \tag{12}$$

The corresponding equations for fatigue life estimation are Eq. (13).

$$N_{34} = \begin{cases} A_3 \cdot S_{\mathrm{re}34}^{-3} & \text{for } S_{\mathrm{re}34} \geq CAFL \\ A_3 \cdot CAFL \cdot S_{\mathrm{re}34}^{-4} & \text{for } S_{\mathrm{re}34} < CAFL \end{cases} \tag{13}$$

For the categories, the values of A_3 and CAFL can be found in the AASHTO specifications.

In ordinary cases, when evaluating the fatigue life of an in-service steel bridge, only a small percentage of stress ranges in a stress histogram are above the CAFL and the computed $S_{\mathrm{re}34}$ would be below the CAFL. Consequently, the segment below of the CAFL with a slope of -4 could conservatively be used from Eq. (14) and Eq. (15) [15].

$$S_{\mathrm{re}4} = \left(\sum_i \frac{n_i}{N} \cdot S_i^4 \right)^{1/4} \tag{14}$$

$$N_4 = A_3 \cdot CAFL \cdot S_{\mathrm{re}4}^{-4} \tag{15}$$

3. APPLICATIONS

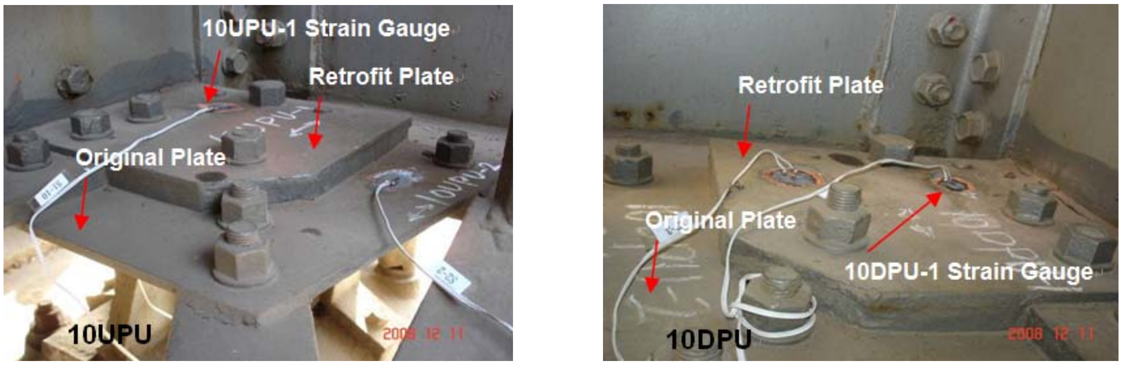
3.1 Wei River Railway Bridge

A railway steel bridge, recorded as No.1 Wei River Railway Bridge and shown in Figure 4, was monitored using field-measurement of live-load stresses at several fatigue-prone structural details. The bridge, built in 1982, is a welded and bolted steel girder bridge with twelve simply supported spans of 26.15m [16]. The monitoring of dynamic stresses under traffic conditions, detailed inspection for crack detection and examination of service traffic were conducted in the years of 2006, 2008 and 2011, for three short time periods.

Figure 4. No.1 Wei River Railway Bridge

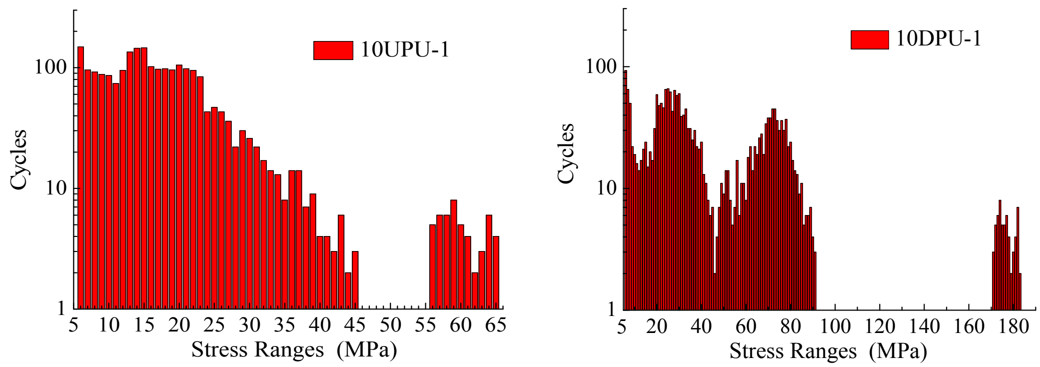
3.1.1 Acquisition of stress range spectra

The photographs of two retrofit gusset plates which were studied are shown in Figure 5. These are 10UPU and 10DPU at the bottom flange connection between the end-panel lateral bracing frames and the main girders. The dynamic stresses in 24 hours and the type of trains, locomotives, carriage number and speed were recorded. The rain-flow counting procedure was used to count the different stress ranges. The live load stress range spectra at strain gauges 10UPU-1 and 10DPU-1 are given in Figure 6. As detail of Category B, the maximum stress range at 10UPU-1 is 64MPa and is below the CAFL of 110 MPa. However, at 10DPU-1 the maximum stress range is 183 MPa and 60 cycles are above the CAFL.



(a) 10UPU-1 (b) 10DPU-1

Figure 5. Strain Measure Points of No.1 Wei River Railway Bridge



(a) Stress Spectrum of 10UPU-1 (b) Stress Spectrum of 10DPU-1

Figure 6. Recorded Stress Spectra of 10UPU-1 and 10DPU-1

3.1.2 Fatigue life evaluation

The equivalent constant amplitude stress ranges, S_{re34} of spectra in Figure 6 are computed using Eq. 12 and Eq. 14 for S_{re34} and S_{re4}, respectively. In addition, the current root-mean-cube (RMC) equivalent stress range in AASHTO specifications for fatigue life evaluation under variable amplitude stress ranges is computed for comparison by using Eq. (16) and Eq. (17).

$$S_{\text{re3}} = \left(\sum_i \frac{n_i}{N} \cdot S_i^3 \right)^{1/3} \tag{16}$$

$$N_3 = A_3 \cdot S_{\text{re}}^{-3} \tag{17}$$

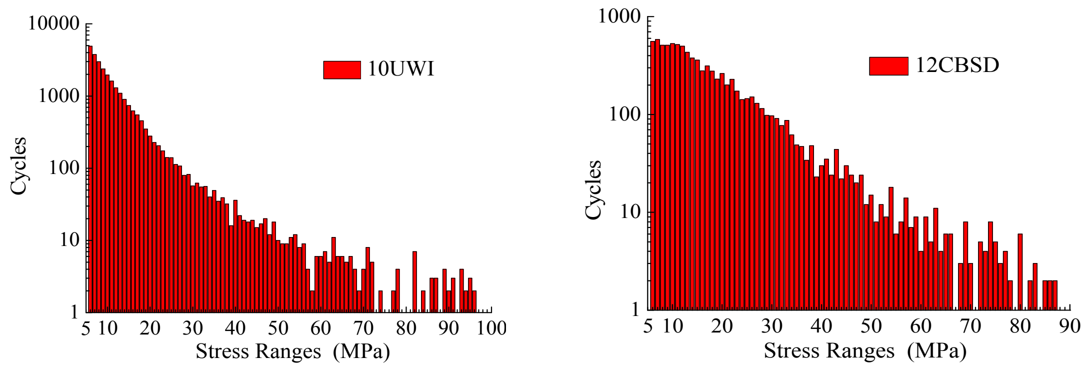
The corresponding estimated fatigue lives are listed in Table 1.

As indicated earlier, all the stress cycles at gauge 10UPU-1 are below the CAFL of category B, so the expected fatigue life is infinite. At gusset plate measure point 10DPU-1, the increases in estimated fatigue life between using a single-sloped S-N line and the bi-linear line are 4.0 and 4.6 million cycles. The ratio of the increased life is 21.9%, and that of is 38.0%. In addition, as illustrated in Table 1, when the majority of stress range cycles in the spectrum are below the CAFL, the estimated fatigue life by using a single S-N line of slope -4 below CAFL is very close to that by the bi-linear curve.

Table 1. Comparison of Estimated Fatigue Life

Detail	Category	N_3 (Mil)	N_{34} (Mil)	N_4 (Mil)	$\frac{N_{34}-N_3}{N_3}$	$\frac{N_{34}-N_4}{N_4}$
10UPU-1	B	Infinite	Infinite	Infinite	-	-
10DPU-1	B	13.7	16.7	12.1	21.9%	38.0%

Other retrofitted details of categories C and D in Wei River Railway Bridge have also been evaluated using bi-linear S-N curves. The live load stress range spectra of two other structural details, 10UWI (Category C) and 12CBSD (Category D), are shown in Figure 7. The corresponding fatigue life evaluation results by using the AASHTO S-N curves and the bi-linear S-N curves are listed and compared in Table 2.



(a) Stress Spectrum of 10UWI (b) Stress Spectrum of 12CBSD

Figure 7. Recorded Stress Spectra of 10UWI and 12CBSD

Table 2. Comparison of Estimated Fatigue Life

Detail	Category	N_3 (Mil)	N_{34} (Mil)	N_4 (Mil)	$\frac{N_{34}-N_3}{N_3}$	$\frac{N_{34}-N_4}{N_4}$
10UWI	C	17.5	22.3	20.1	27.4%	10.9%
12CBSD	D	15.7	18.7	15.2	19.1%	23.0%

From the results listed in Table 2, the evaluation based on bi-linear fatigue S-N curves with different slopes above and below the CAFL always predicts a longer fatigue life compared to that based on the single slope AASHTO S-N curves. The increase of estimated fatigue life can be quite significant. For the category C detail 10UWI, the increase is 4.8 million cycles and the increased life ratio is 27.4%. For the category D detail 12CBSD, the increase is 3.0 million cycles and the increased life ratio is 19.1%. For the 3 details listed in Tables 1 and 2, using bi-linear fatigue S-N curves compared to using the current AASHTO S-N curves results in at least a 19.1% increase of fatigue life. This suggests that it may be unnecessary to take rehabilitation action at some structural details, which could reduce the maintenance fee and life-cycle cost.

To examine the evaluation of fatigue life by the Eurocode S-N curves, the fatigue life of the 3 details are calculated according to the procedure of Eurocode 3. The procedure of using RMC as the equivalent constant amplitude stress range is in essence the extension of slope -3 down to below the CAFL without considering the portion of the S-N curves with a slope of -5. And ignoring of all stress data below the horizontal cut-off limit means ignoring the contribution of those stress cycles to the growth of the fatigue crack. Consequently, it is expected that the estimated fatigue life by using the suggested procedure for the bi-linear Eurocode S-N curves is longer than that by the suggested bi-linear S-N curves for AASHTO. This is the case for all four details of the Wei River Railway Bridge as listed in Table 3.

It is suggested that a set of equations for the bi-linear S-N curves with the break at the CAFL be used for the Eurocode 3. The slopes above and below CAFL of S-N curves are -3 and -5, respectively. From Eq. (11), the equivalent constant amplitude stress range S_{re35} can be expressed as Eq. (18).

$$S_{\mathrm{re35}}=\begin{cases}\left(\sum_i \frac{n_i}{N}\cdot S_i^3+\frac{\sum_j \frac{n_j}{N}\cdot S_j^5}{(CAFL)^2}\right)^{1/3} & \text{for } S_{\mathrm{re35}}\ge CAFL\\ \left[(CAFL)^2\cdot\sum_i \frac{n_i}{N}\cdot S_i^3+\sum_j \frac{n_j}{N}\cdot S_j^5\right]^{1/5} & \text{for } S_{\mathrm{re35}}< CAFL\end{cases} \tag{18}$$

The corresponding equations for the estimation of fatigue life is Eq. (19).

$$N_{35}=\begin{cases}A_3\cdot S_{\mathrm{re35}}^{-3} & \text{for } S_{\mathrm{re35}}\ge CAFL\\ A_3\cdot(CAFL)^2\cdot S_{\mathrm{re35}}^{-5} & \text{for } S_{\mathrm{re35}}< CAFL\end{cases} \tag{19}$$

In most cases, when evaluating the fatigue life for in-service steel bridges, only a small percentage of stress ranges are above the CAFL and the computed S_{re35} would be below the CAFL. Consequently, the segment below of the CAFL with a slope of -5 could conservatively be used from Eq. 20 and Eq. 21.

$$S_{\mathrm{re5}}=\left(\sum_i \frac{n_i}{N}\cdot S_i^5\right)^{1/5} \tag{20}$$

$$N_5=A_3\cdot(CAFL)^2\cdot S_{\mathrm{re5}}^{-5} \tag{21}$$

The procedure of using the bi-linear line with slopes of -3 and -5, and ignoring the damage contribution of stress ranges below the horizontal cut-off limits. Table 3 shows the comparison between the calculated fatigue lives. From Table 3, it is obvious that the estimated fatigue life by using bi-linear line with slopes of -3 and -5 (L_{35}) is close to Eurocode 3 approach(L_{euro}), both of which are slightly longer than by using the suggested bi-linear S-N curves for AASHTO (L_{34}).The suggested procedure of the bi-linear L_{35} is less conservative in fatigue life evaluation compared to using the bi-linear S-N curves with the slopes of -3 and -4 (L_{34}) and the current AASHTO S-N curves.

Table 3. Comparison of Estimated Fatigue Life

Detail	Category	L_{35} (Year)	L_{euro} (Year)	L_{34} (Year)	$\frac{L_{35}-L_{euro}}{L_{euro}}$	$\frac{L_{35}-L_{34}}{L_{34}}$
10DPU-1	B	92	88	80	4.5%	15.0%
10UWI	C	211	217	179	-2.8%	17.9%
12CBSD	D	85	93	75	-8.6%	13.3%

3.2 Wei River Freeway Bridge

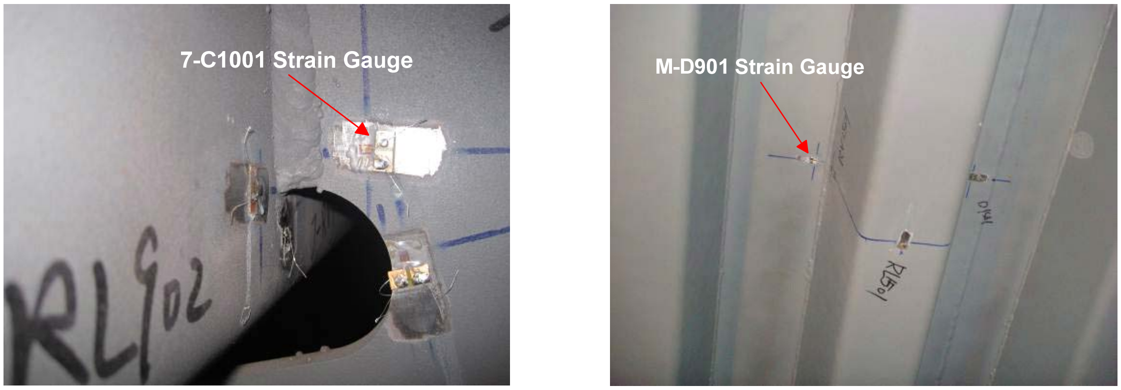
To further apply and analyze the bi-linear S-N curves for fatigue life evaluation for in-service bridges, a freeway bridge, named as Wei River Freeway Bridge shown in Figure 8, was monitored by field-measurement of live load stress at several fatigue-prone structural details in orthotropic steel bridge deck. Wei River Freeway Bridge, built in 2011, is a continuous concrete bridge as a whole while a 53.68m steel girder is adopted at side span to optimize the overall structural behavior. Since there are many fatigue details in OSDs [17], a twelve-day dynamic stress monitoring under traffic conditions were conducted in 2013 to evaluate the fatigue performance of the structure.

Figure 8. Wei River Freeway Bridge

3.2.1 Acquisition of stress range spectra

The photographs of two fatigue details which were studied at the case of Wei River Freeway Bridge are shown in Figure 9. The strain gauge 7-C1001 is at the end of rib-to-diaphragm in a diaphragm. The strain gauge M-D901 is at the weld joint of rib-to-deck in a deck plate. The dynamic stresses, the number and type of trucks were recorded. The rain-flow counting procedure was used to count the different stress ranges.

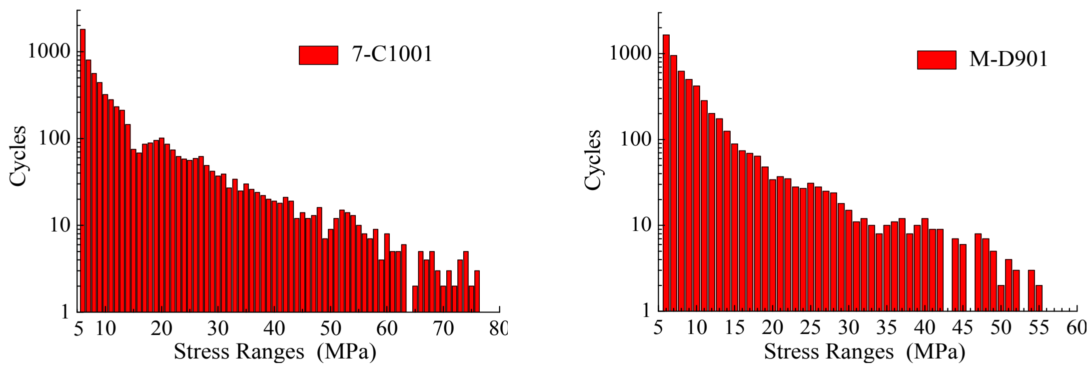
However, Wei River Freeway Bridge is a part of a new freeway open to traffic since December, 2011. This newly built freeway is planned to have more branches, but at this stage it just connect Xi'an city and Tongchuan city. Meanwhile, there is an old in-service freeway nearby, and the old one has more branches and cheaper tolls. Thus, the traffic volume of the new freeway is relatively small at present, and the average daily truck volume is about 500.



(a) 7-C1001 (b) M-D901

Figure 9. Strain Measure Points of Wei River Freeway Bridge

The resulting live load stress range spectra at strain measure points 7-C1001 and M-D901 are given in Figure 10. The maximum stress ranges at 7-C1001 and M-D901are 78MPa and 57MPa, respectively.



(a) Stress Spectrum of 7-C1001 (b) Stress Spectrum of M-D901

Figure 10. Recorded Stress Spectra of 7-C1001 and M-D901

3.2.2 Fatigue life evaluation

The estimated fatigue lives for the details in Figure 9 are calculated using Eq. 13, Eq. 15 and Eq. 17 for N_3, N_{34} and N_4, and, respectively. The corresponding life L_3, L_{34} and L_4 are listed and compared in Table 4.

Table 4. Comparison of Estimated Fatigue Life

Detail	Category	N_3 (Mil)	L_3 (Year)	N_{34} (Mil)	L_{34} (Year)	N_4 (Mil)	L_4 (Year)	$\frac{L_{34}-L_3}{L_3}$	$\frac{L_4-L_{34}}{L_{34}}$
7-C1001	C	21.0	93	29.7	131	29.3	129	40.9%	-1.5%
M-D901	D	22.6	118	29.5	154	28.8	151	30.5%	-1.9%

At 7-C1001, the increase in estimated fatigue life between using a single-slope S-N curve and the bi-linear curve is 131-93=38 years. The ratio of the increased life $(L_{34}-L_3)/L_3$ is 40.9%. At M-D901, the ratio of $(L_{34}-L_3)/L_3$ is 30.5%. It is also proved that the evaluation based on bi-linear fatigue S-N curves with different slopes above and below the CAFL will predict a longer fatigue life compared to that based on the single slope AASHTO S-N curves. In addition, compared to single slope of -4, the decreased life ratio of the bi-linear S-N curve approach $(L_4 - L_{34})/L_{34}$ is -1.5% and -1.9%.

To examine the proposed bi-linear S-N curves for Eurocode 3, the estimated fatigue lives for 7-C1001 and M-D901 are calculated using Eq. 19 for N_{35}. The corresponding L_{35} is compared with L_{euro} and L_{34} in Table 5. From Table 5, it is obvious that the estimated fatigue life by using bi-linear curves with slopes of -3 and -5 (L_{35}) is longer than by using the suggested bi-linear S-N curves for AASHTO (L_{34}).

Table 5. Comparison of Estimated Fatigue Life

Detail	Category	L_{35} (Year)	L_{euro} (Year)	L_{34} (Year)	$\frac{L_{35}-L_{euro}}{L_{euro}}$	$\frac{L_{35}-L_{34}}{L_{34}}$
7-C1001	C	170	162	131	4.9%	29.8%
M-D901	D	189	201	154	-6.0%	22.7%

4. SUMMARY AND CONCLUSIONS

This paper provides information for fatigue life evaluation of in-service steel bridges by integrating field-measured live-load stresses into the bi-linear S-N curves with a break at the constant amplitude fatigue limit (CAFL). The current procedure of AASHTO specifications, with a direct extension of S-N curves to below the CAFL, appears to be too conservative. The slopes of suggested bi-linear S-N curves for the AASHTO specifications are -3 and -4, while for the Eurocode are -3 and -5. Equations for the calculation of the equivalent constant amplitude stress range are presented and applied.

From this study, the following conclusions can be drawn:

(1) Compared to the estimated fatigue life using the current single-slope AASHTO S-N curves, applying the bi-linear S-N curves always results in a longer fatigue life for the structural details in a bridge.

(2) When the majority of stress range cycles in a stress spectrum are below the CAFL, the calculated fatigue life by using only the portion of S-N curves below the CAFL can be close to that by using bi-linear curves.

(3) The estimated fatigue life by using the suggested procedure for the bi-linear Eurocode S-N curves is always longer than that by using the suggested bi-linear S-N curves for AASHTO. This is due to the difference in slope below the CAFL.

(4) There are only limited data of long time or high cycle fatigue damage due to variable stresses. Development of such data is recommended.

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